

# Sealing is at the Origin of Rubber Slipping on Wet Roads

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Loss of braking power and rubber skidding on a wet road is still an open physics problem, since neither the hydrodynamical effects nor the loss of surface adhesion that are sometimes blamed really manage to explain the 20 – 30% observed loss of low speed tire-road friction. Here we advance a novel mechanism based on sealing of water-filled substrate pools by the rubber. The sealed-in water effectively smoothens the substrate, thus reducing the viscoelastic dissipation in bulk rubber induced by surface asperities, well established as a major friction contribution. Starting with the measured spectrum of asperities one can calculate the water-smoothened spectrum and from that the predicted friction reduction, which is of the right magnitude. The theory is directly supported by fresh tire-asphalt friction data.

First principle calculations of frictional forces for realistic systems are generally impossible. The reason is that friction usually is an interfacial property, often determined by the last few uncontrolled monolayers of atoms or molecules at the interface. An extreme illustration of this is offered by diamond. The friction between two clean diamond surfaces in ultra high vacuum is huge because of the strong interaction between the surface dangling bonds. However, when the dangling bonds are saturated by a hydrogen monolayer (as they generally are in real life conditions), friction becomes extremely low[1]. Since most surfaces of practical use are covered by several monolayers of contaminant molecules of unknown composition, a quantitative prediction of sliding friction coefficients is out of the question. An exception to this may be rubber friction on rough surfaces, which is the subject we address here.

Rubber friction is of extreme practical importance, e.g., in the context of tires, wiper blades, conveyor belts and sealings[2]. Rubber friction on smooth substrates, e.g., on smooth glass surfaces, has two contributions, namely an adhesive (surface) and a hysteretic (bulk) contribution[2, 3]. The adhesive contribution results from the attractive binding forces between the rubber surface and the substrate. Surface forces are often dominated by weak attractive van der Waals interactions. For very smooth substrates, because of the low elastic moduli of rubber-like materials, even when the applied squeezing force is very gentle this weak attraction may result in a nearly complete contact at the interface[4, 5], leading to the large sliding friction force usually observed[6]. For rough surfaces on the other hand the adhesive contribution to rubber friction will be much smaller because of the small contact area. The actual contact area between a tire and the road surface, for example, is typically only  $\sim 1\%$  of the nominal footprint contact area[7, 8]. Under these conditions the bulk (hysteretic) friction mechanism is believed to prevail. The substrate asperities exert pulsating forces on the rubber. A large internal friction at the appropriate frequencies causes a large energy dissipation in the rubber bulk, and that in turn provides the main source of friction[7, 8]. For example, the exquisite sensitivity of tire-road friction to temperature just reflects the strong temperature dependence of the viscoelastic bulk properties of rubber.

The bulk nature of rubber-rough substrate friction is also the key that permits its quantitative characterization and calculation. In fact, we showed recently that the observed sliding friction of a tire on a dry road surface can be calculated quite accurately by assuming it to be due entirely to internal damping in the rubber[7]. This theory takes into account the pulsating forces acting on the rubber surface from road asperities from all length scales, from  $\lambda_0 \sim 1$  cm, corresponding to the largest road asperities, down to micro-asperities characterized by a wavelength  $\lambda_c$  of order  $\sim 1 \div 10$   $\mu\text{m}$  (theory shows that shorter wavelength roughness is unimportant). It gives friction coefficients of order unity, as are indeed observed experimentally.

Our focus here is on rubber friction on *wet* rough substrates, where at low sliding velocities it is known that the friction typically drops by as much as 20–30% relative to the dry case[9, 10]. Owing to the small contact area, this cannot be the result of a water-induced change of adhesion. On the other hand, as will be discussed below, the friction decrease cannot be blamed on a purely hydrodynamical effect either. That leaves finally the possibility that water might change precisely the bulk, hysteretic friction. We propose here that this is indeed the case. Water pools that form in the wet rough substrate are *sealed off* by the rubber, as sketched in Fig. 1, and that will effectively smoothen the substrate surface. Smoothing reduces the viscoelastic deformation from the surface asperities, and thus reduces rubber friction.

Rubber friction from the viscoelastic deformation by the substrate asperities is determined by the complex frequency-

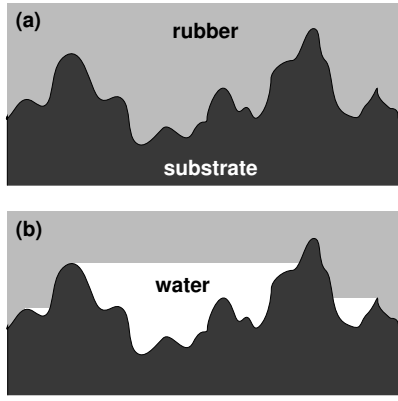


FIG. 1: A rubber block sliding on a rough hard substrate. (a) On a dry substrate the rubber penetrates a large valley and explores the short wavelength roughness within. The pulsating rubber deformations induced by the short-wavelength roughness contributes to the friction force. (b) On a wet substrate the valley turns into a water pool. Sealing of the pool prevents the rubber from entering the valley. By removing the valley contribution to the frictional force, the sealing effect reduces the overall sliding friction.

dependent bulk viscoelastic modulus  $E(\omega)$  of rubber and by the substrate surface roughness power spectrum  $C(q)$ . If  $h(\mathbf{x})$  is the substrate height profile (measured from the average surface plane  $\langle h \rangle = 0$ ), then

$$C(q) = \frac{1}{(2\pi)^2} \int d^2x \langle h(\mathbf{x})h(\mathbf{0}) \rangle e^{-i\mathbf{q}\cdot\mathbf{x}}. \quad (1)$$

Fig. 2(a) presents the height contour lines measured for a  $1.5 \text{ cm} \times 1.5 \text{ cm}$  square of dry asphalt road.

Assuming isotropic and translationally invariant statistical properties for the substrate,  $C(q)$  will only depend on the magnitude  $q = |\mathbf{q}|$  of the wavevector  $\mathbf{q}$ . The upper curve in Fig. 3 shows the power spectrum extracted via Eq. (1) from the measured height profile  $h(\mathbf{x})$ . The log-log scale shows that for  $q > 1600 \text{ m}^{-1}$ ,  $C(q)$  drops as a power law, as expected for a self-affine fractal surface. The fractal dimension of this surface is determined by the slope of the curve in Fig. 3 (which equal  $2D_f - 8$ , where  $D_f$  is the fractal dimension) and is about  $D_f = 2.2$ , and the root-mean-square roughness can be obtained directly from the height profile,  $h_{\text{rms}} \approx 0.3 \text{ mm}$ .

The roll-off wavevector  $q_0 = 1600 \text{ m}^{-1}$  below which  $C(q)$  is constant corresponds to the size  $\lambda_0 = 2\pi/q_0 \approx 4 \text{ mm}$  of the largest asperities or sand particles, etc., contained in the asphalt. Hysteretic rubber friction will of course decrease with decreasing magnitude of  $C(q)$ . Depending on the sliding velocity  $v$  it will also sample differently the wavevector dependence of  $C(q)$  over a wide range of  $q$ . For example, rubber friction on asphalt surfaces at typical car velocities depends on  $C(q)$  for  $q_1 < q < q_2$ , where  $q_1 \approx 10^3 \text{ m}^{-1}$  and  $q_2 \approx 10^6 \text{ m}^{-1}$ .

Consider now a tire rolling and sliding on a wet road surface. At low velocities (say  $v < 60 \text{ km/h}$ ) there will be negligible hydrodynamic water buildup between the tire and the road surface. In essence[11], if  $v < (\sigma/\rho)^{1/2}$ , where  $\sigma$  is the perpendicular stress in the tire-road contact area and  $\rho$  the water mass density, there is sufficient time for the water to be squeezed out of the contact regions between the tire and the road surface, except for water trapped in road cavities. The water pools will be sealed off by the road-rubber contact at the upper boundaries of the cavities (see Fig. 1). Thus, in what follows we will focus on the smoothening effect on the road profile caused by the sealing.

Starting from a dry substrate profile  $h(\mathbf{x})$  we can numerically build a new wet surface height profile  $h'(\mathbf{x})$  as shown in Fig. 2(b). The algorithm assumes every valley to be filled with water up to the maximum level where the water will remain confined, i.e., up to the lowest point of the edge surrounding the pool. The square size  $D$  is assumed to be that of a tread block, so that any extra water added to the profile of Fig. 2(b) will flow straight out of the square area. If  $D > \lambda_0$ , as is the case in our data, this construction is unique. (Even if  $D < \lambda_0$  uniqueness can still be attained at the price of averaging over many realizations).

From the water-smoothened height profile  $h'(\mathbf{x})$  we obtain a modified power spectrum  $C'(q)$  shown by the lower curve in Fig. 3. While the fractal power-law decay and the roll-off wavevector are essentially the same as for the dry surface, the reduction in the power spectrum reflect the effective water-induced smoothening of the rough substrate.

The sealed-off water in the pools (see Fig. 1) removes contact with the interior of the valley, which smoothenes the effective substrate roughness profile. Our basic assumption is therefore that when rubber slides on the wet rough surface, the friction force will be determined by the modified power spectrum  $C'(q) < C(q)$ .

Let us now examine, based on this model, numerical results on tire friction on dry and wet substrates, calculated using the hysteretic friction theory presented in Ref. [7]. The hysteretic friction coefficient at velocity  $v$  is determined

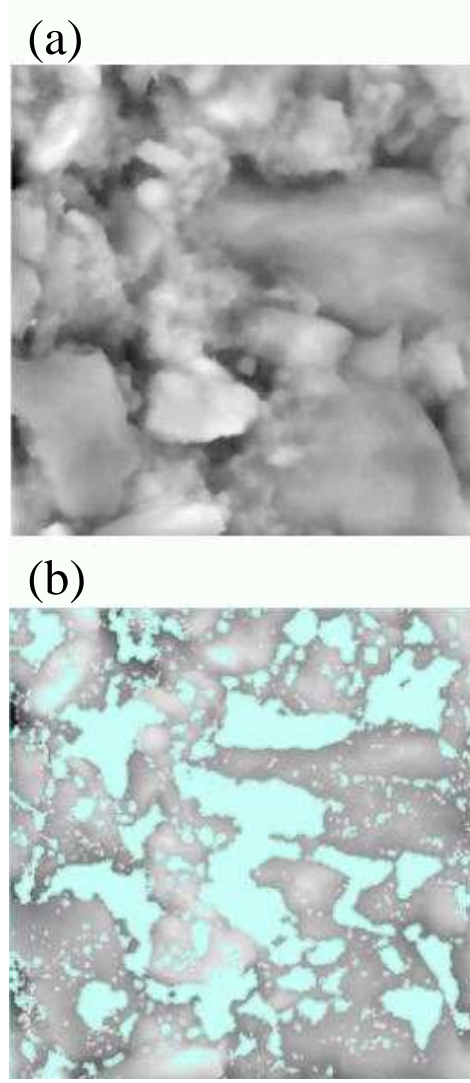


FIG. 2: Water smoothing of road roughness. (a) Optically measured height profile of a dry asphalt road ( $1.5 \text{ cm} \times 1.5 \text{ cm}$  area). Darker areas correspond to deeper regions. (b) Calculated wet profile for the same area, with water pools (light blue).

by knowledge of the rubber viscoelastic modulus  $E(\omega)$  and of the surface roughness spectrum  $C(q)$  by

$$\mu_k = \frac{1}{2} \int dq q^3 C(q) P(q) \int_0^{2\pi} d\phi \cos\phi \operatorname{Im} \frac{E(qv \cos\phi)}{(1 - \nu^2)\sigma},$$

where  $\operatorname{Im}$  denotes the imaginary part of the complex Young modulus  $E$  and  $\phi$  is the angle between  $\mathbf{q}$  and  $\mathbf{v}$ . Moreover

$$P(q) = \frac{2}{\pi} \int_0^\infty dx \frac{\sin x}{x} \exp[-x^2 G(q)] = \operatorname{erf}(1/2\sqrt{G}),$$

where  $\operatorname{erf}$  is the error function, and

$$G(q) = \frac{1}{8} \int_0^q dq q^3 C(q) \int_0^{2\pi} d\phi \left| \frac{E(qv \cos\phi)}{(1 - \nu^2)\sigma} \right|^2,$$

where  $\sigma$  is the mean perpendicular pressure (load divided by the nominal contact area), and  $\nu$  the Poisson ratio, which equals 0.5 for rubber-like materials.

We obtained in this way quantitative results for the friction of a standard tread compound, sliding on the asphalt road just characterized. We used the measured rubber complex viscoelastic modulus (not shown) along with the power spectra presented in Fig. 3 for the dry and for the wet road surfaces.

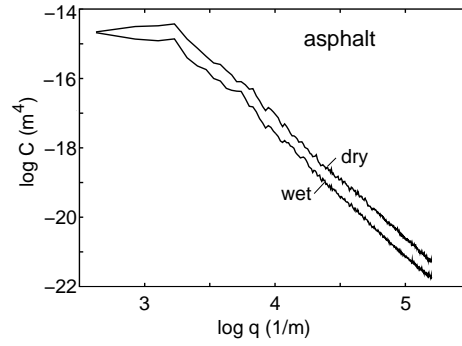


FIG. 3: Surface roughness power spectra  $C(q)$  (above) extracted from the measured height profile for a dry asphalt road surface, and (below) calculated assuming sealing of all pools in the same surface when wet, as in Fig. 1. Note the logarithmic scales.

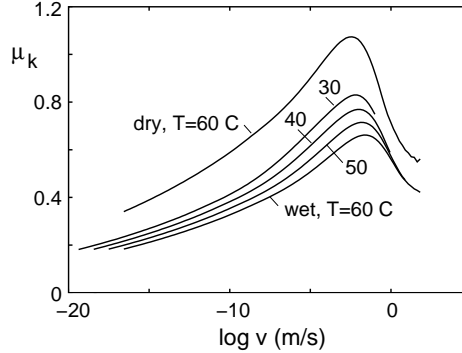


FIG. 4: Kinetic friction coefficient as a function of the logarithm of the sliding velocity, calculated for a standard tread compound and an asphalt substrate with the roughness spectra of Fig. 3.

Fig. 4 shows the rubber-asphalt kinetic friction coefficient calculated for the dry surface at  $T = 60^\circ \text{C}$  as a typical tire temperature while rolling on a dry road, and for the wet surface at four different temperatures, namely  $T = 30, 40, 50$ , and  $60^\circ \text{C}$  (on a wet road the tyre temperature is typically  $30^\circ \text{C}$ , and generally lower than on the dry surface). Calculations include the flash temperature generated by the local energy dissipation, shifting the rubber viscoelastic spectra toward the rubbery region. This effect is important at sliding velocities  $v > 1 \text{ cm/s}$ . Also, the decreasing friction with increasing temperature shown in Fig. 4 is commonly observed for rubber. The viscoelastic spectrum shifts to higher frequencies with increasing temperature, making rubber more elastic and less viscous, and reducing friction.

When dry and wet frictions are compared, the calculation shows first of all a water-induced friction decrease of  $\sim 30\%$  at  $T = 60^\circ \text{C}$ . The decrease becomes somewhat less ( $\sim 20\%$ ) if the wet substrate temperature is (realistically) reduced to  $T = 30^\circ \text{C}$ . We also calculated  $\mu$ -slip curves[9, 10], which show a very similar reduction in the friction for wet road surfaces, in excellent agreement with the known reduction of low-speed rubber friction on road surfaces.

The above picture does in our view catch an important novel effect of water on rubber friction. Yet, it is open to refinements in various ways. First, dry friction of tires is not pure sliding but also involves some stick-slip[12]. This effect is included in the calculation of  $\mu$ -slip curves, and the observed reduction in the effective friction is similar to that in Fig. 4. Second, after enough time all sealings leak. This will be particularly true in the present case because the upper boundary of a water filled pool, which is in contact with the rubber, still has roughness on many length scales. So one cannot expect the rubber to make equally perfect contact everywhere, and there will be narrow channels through which the water slowly seeps out of the pools. As a result, for sufficiently low sliding velocities the negative water influence on rubber friction may revert to negligible. Experiments indeed show that to be the case for extremely low speed below  $0.7 \text{ m/s}$ , where the difference in  $\mu_k$  between dry and wet surfaces is very small[12]. We should also stress that the effects addressed here clearly apply only to moderately wet substrates and for speeds below  $60 \text{ km/h}$ . For flooded surfaces, or for tires without a tread profile and speeds above  $60 \text{ km/h}$  aquaplaning may occur, which originates instead from the inertia of the water. Finally, for rubber friction on relative smooth wet surfaces, where the adhesional interaction is important, the so called dewetting transition[13, 14, 15] may be important.

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